Experimental Study on Compressibility, Volume Changes, Strength and Permeability Characteristics of Unsaturated Bentonite-Sand Mixtures

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ABSTRACT

Expansive soils are generally found in arid and semiarid regions. These soils undergo volumetric changes upon wetting and drying, thereby causing ground heave and settlement problems. This characteristic causes considerable construction defects if not adequately taken care of. Solving the unsaturated soil problems needs the assessment of suction variation in time and space as a response to the variation of environmental factors such as rainfall and evaporation.

To investigate the effect of the changes of the soil suction on the volume changes, expansion index, swelling pressure, shear strength and the coefficient of permeability, small scale experiments were conducted using pure bentonite and the bentonite mixed with sand in proportion of: 30%, 40% and 50% at different initial water contents and dry unit weights was chosen from the compaction curves. The study shows that the swelling potential, swelling pressure, the soil suction, the soil strength and the coefficient of permeability are affected by the initial conditions (water content and dry unit weight), where all these parameters except the permeability coefficient marginally decrease with the increase in soil water content, while the coefficient of permeability increases with increasing the water content.

Keywords: Expansive soils, volumetric changes, soil suction, swelling pressure, shear strength.

INTRODUCTION

In geotechnical engineering practice, conventional soil mechanics principles are utilized for the design of the foundations assuming that the soil is in a state of saturated condition (pores filled with water). However, in many situations, natural soils are found in a state of unsaturated condition (pores filled with a mixture of air and water) as the ground water table is at a great depth. This is especially valid for soils in arid and semi-arid regions. A few geotechnical structures such, as, high-ways, embankments, dams are constructed on or with compacted unsaturated soils in which the foundations may be placed. The stresses associated with these foundations are distributed within the unsaturated soil zone above the ground water table (Vanapalli and Taylan, 2012).

In Iraq, the expansive soil spreads in substantial zones in the north, south, and the middle parts. Damages can occur within a few months following construction or may develop gradually over a period of about five years, or may not appear for many years until some activity occurs to disturb the soil moisture. Moisture changes within soil happen when water is removed from the soil by either evaporation or evatranspirtion from the vegetative cover. These processes cause an upward flux of water out of the soil, while rainfall and other form of precipitation produce a downward flux of water into the soil (Fredlund and Rahardjo, 1993).

Several researchers conducted investigations on expansive and unsaturated soils, Agus*et al.* (2010) focused on investigating suction characteristics of bentonite-sand mixtures. Suction was measured using various techniques (Filter paper, Psychrometer, Dew point sensor and Chilled-mirror hydrometer) for compacted bentonite-sand mixtures. The laboratory results were analyzed to provide an understanding of the suction concept in expansive soils. It was found that suction depends primarily on the water content and the bentonite content of the mixture, and suction in expansive soils changes with hydration time and it is not influenced by the fabric (void ratio)or the pore geometry.

Baille*et al.* (2010) determined the swelling pressure of the compacted bentonite. Constant volume swelling pressure tests were performed on 4 different clays. The bentonite sorts used were chosen to cover an extensive variety of sodium content and of initial porosity. For each bentonite, specimens of 3 different initial dry densities changing from 1.24 up to 1.66 g/cm³ were tested. The initial water content relates to the water content of the clays at laboratory ambient conditions (T = 20.5 °C, RH ≈ 50%), and hence varied slightly around 4.6 %. Only two specimens approximately with w = 3.84% and 6.69% water content, respectively were used. The results indicated that the swelling pressure of the compacted bentonites increase with increasing the dry density.

Sun *et al.* (2010) carried out laboratory testing on a heavily compacted sand-bentonite mixture. To measure the SWRC (soil water retention curve) of the mixture over a large range of suction, a pressure plate apparatus and filter papers were used. The obtained SWRC shows that the measurements via the two methods consistently agree with each other. By using a suction-controlled oedometer for unsaturated soils, a series of one-dimensional compression tests were performed on the unsaturated compacted sand-bentonite mixture at different constant suctions. The testing results indicated that the yield stress increases and compression index decreases with the increase of imposed suction. The results also exhibited that the mixture wetted to saturation and subsequently dried to a certain suction level has a lower yield stress than that wetted directly to the same suction.

Al-Lami (2014) performed a research on expansive (bentonites and sand mixture) and non-expansive (kaolin) with various water contents and dry unit weights chosen from the compaction curve to examine the effect of water content change on soil properties (swelling pressure, expansion indices, shear strength (soil cohesion) and soil suction by the filter paper method) for the small soil samples. Large scale model was also used to show the effect of water content change on different relations (swelling with time, suction with time, bearing capacity of shallow footing …).The soil water retention curve (SWRC) was measured in this study by two methods (the filter paper and tensiometer). The fitting equations in the (Soil Vision) program were used after inserting the required soil properties (specific gravity, dry unit weight, gravimetric water content, grain size analysis and at least three points of suction with the corresponding water content). The study revealed that the initial soil conditions (water-content, and, dry, unit, weight) affect the soil cohesion, soil suction and soil swelling, where all these parameters marginally decrease with the increase in soil water content especially on the wet side of optimum.

The main objective of the present study is to increase the understanding of the mechanics of unsaturated particulate materials by modeling the behavior of the expansive soil in the framework of unsaturated soil mechanics. This work is directed to predict the volume changes, swelling pressure, shear strength and the coefficient of the permeability associated with the changes in soil suction. Different mixture of Bentonite-sand is used to get different degree of expansion.

Experimental Work

This section describes the materials utilized for the experimental part of the research, the experimental apparatus, and procedures adopted for laboratory testing.

Soil used

Four types of soil were employed for testing to evaluate the effect of suction on volume change and shear behavior of unsaturated clay soil in order to provide a comparison between them.

The first soil is pure bentonite and it was brought from Al-Rutba city in Al-Anbar governorate while the other types of soil sample were prepared in the laboratory by mixing the bentonite with different proportions of sand (70:30, 60:40, 50:50 bentonite:sand)% of dry weight. The sand used in the study was obtained from Al-Ekhether city 50 km south-west Karbala and 152 km south-west Baghdad.

Standard tests were performed to determine the physical properties, activity, classifications and chemical properties of each soil and the results are summarized in Tables (1) and (2). Table (3) illustrates the classification of soils according to different criteria.

The grain size distribution (sieve analysis and hydrometer test) for the four types of soil and the dry sieving for the sand which was performed according to ASTM D 422-02 and ASTM D 1140-00 specifications is shown in Figure (1), the classification of soils is summarized in Table (1).

Figures (2) to (5) represent the standard compaction (Proctor test) curves of the soils used in the study, the test was done according to ASTM/D 698-12. The compaction increases the soil strength and bearing capacity and decreases the permeability, compressibility and the soil shrinkage because of the reduction in the soil void ratio.

The optimum moisture content for pure-bentonite is the highest as compared with other soils as demonstrated in Figure (2) because bentonites is known as having higher sportive forces since bentonite has surface electrical charges.The addition of sand tothebentonitedecreases thewatercontentbyreducingthesurfaceareaarresponsibleforabsorbingwaterascomparedto pure bentonite. In addition the dry unit weigh to bentonite increases with the sand addition depending on the particle size distribution and the coefficient of uniformity of the soil(Aguset al., 2010).

Table (1): The chemical properties of soils used.

Chemical properties	Bentonite	Sand
SO_3 Content (%)	2.42	0.113
Organic Matter (O.M.) (%)	0.62	0.06
Gypsum (%)	5.2	0.24
Total Soluble Salt (TSS) (%)	6.3	0.14
pH Value	9.12	8.58

Table (2): Physical properties of soils used.

Physical Properties	Bentonite	Sand	B:S 70:30	B:S 60:40	B:S 50:50	Specification
Specific gravity (Gs)	2.84	2.74	2.81	2.8	2.79	ASTM D 854
Liquid Limit (L.L)	123	NP	87	73	48	ASTM D 4318
Plastic Limit (P.L)	42	NP	28	27	18	ASTM D 4318
Plasticity Index (P.I)	81	NP	59	46	30	ASTM D 4318
% clay	75	1.6	56	48.5	38	ASTM D 1140, D 422.
% silt	22.5		14.3	11.5	10.3	
% sand	2.5	98.4	29.7	40	51.7	
Activity (A) %	1.08	---	1.05	0.95	0.79	Head, (2006)
Optimum Moisture Content % (O.M.C)	34	----	27	22	18	ASTM D 698-12
Maximum Dry Unit Weight $(\gamma_{dry})_{max}$ (kN/m³)	12.75	18.4	15.1	15.9	16.6	ASTM D 698-12
Minimum Dry Unit Weight (kN/m³)	---	15.75	---	---	---	ASTM D 4254
Void Ratio (e) at O.M.C	1.227	0.489	0.861	0.761	0.681	---
Soil Symbols according to USCS	CH	SP	CH	MH	SM	ASTM D 2487

Table (3): Classification of expansion potential of soils according to different criteria.

Soil Criteria	Pure Bentonite	B:S 70:30	B:S 60:40	B:S 50:50
Al-Rawas and Goosen, (2006) (L.L, P.L)	Very high	Very high	Very high	Medium
Al-Rawas and Goosen,(2006) (Clay content, P.I)	Very high	Very high	Very high	High
Al-Rawas and Goosen,(2006) (Swelling potential)	High*	High*	Medium*	Medium*
Day, (1994) (Expansion Index)	Very high*	High*	Low*	Low*
Day, (1994) (Clay content)	Very high*	Very high*	Very high*	Very high*
Day (1994) (Swelling %)	Very high*	High*	Medium*	Low*
Sivapullaih*et al.*(1996) (Modified free swell index)	Very high	High	High	Moderate

* The results were taken at the O.M.C and maximum dry unit weight.

According to ASTM D 4254, coefficient of uniformity (Cu) and coefficient of curvature (Cc) is 0.92 and 2.67, respectively for poorly graded sand.

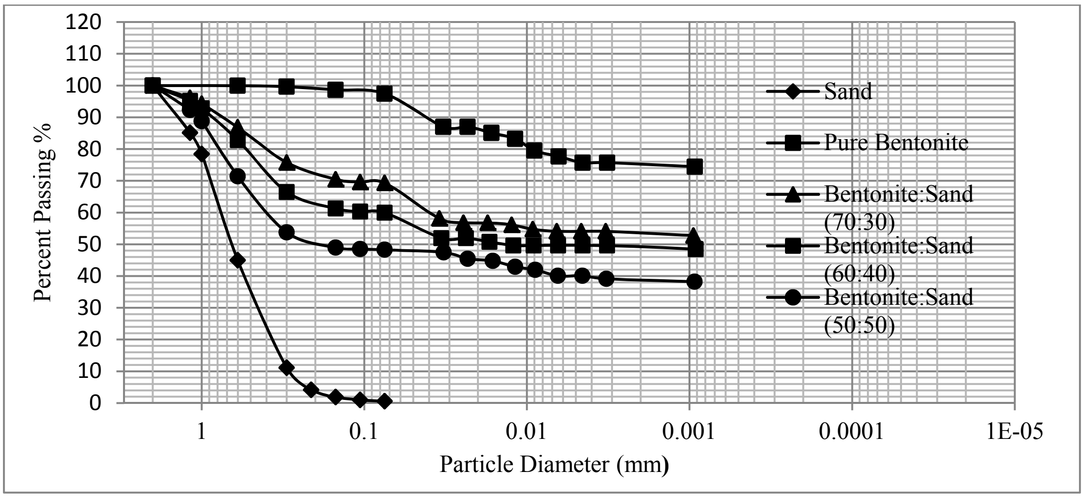

Figure (1): The grain size distribution for the soil used.

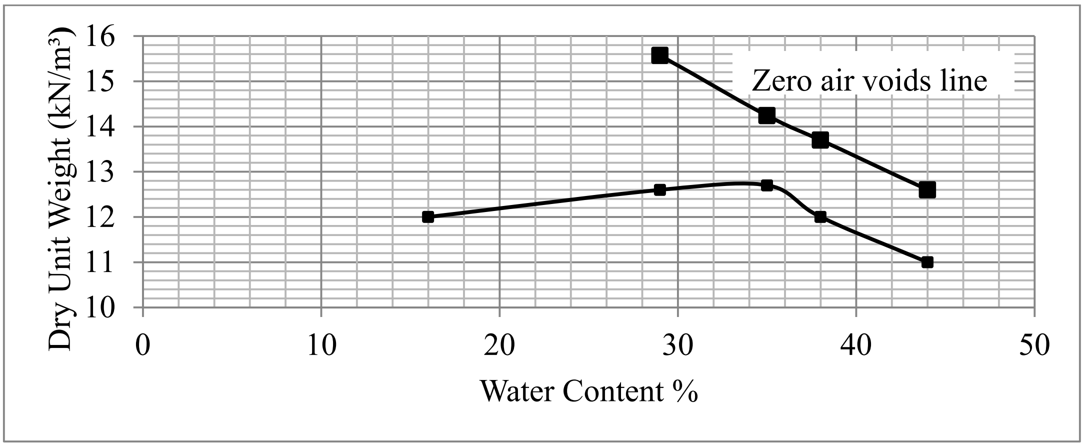

Figure (2): Compaction curve of bentonite soil

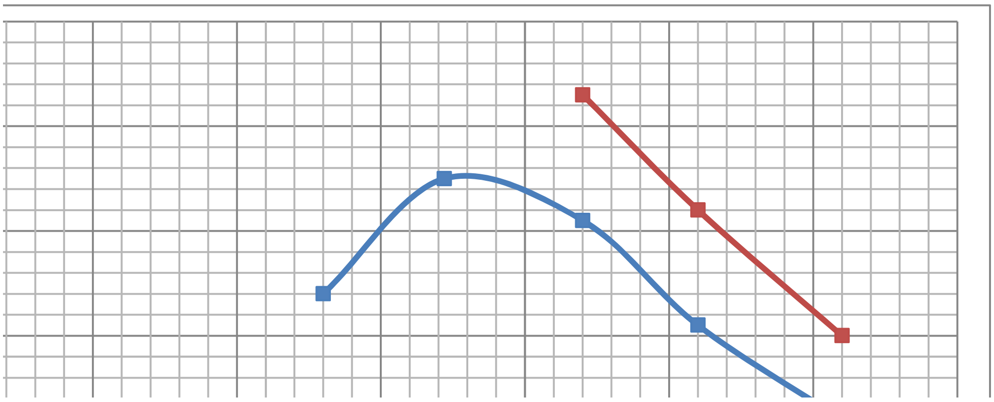

Figure (3):Compaction curve of bentonites-sand soil with proportion70:30.

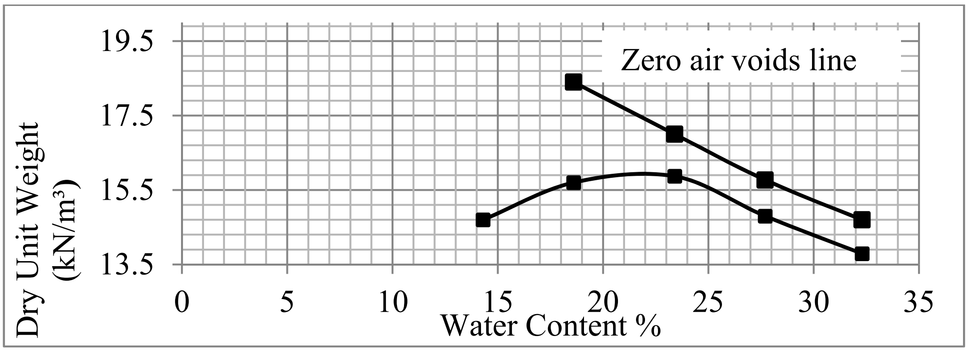

Figure (4): Compaction curve of bentonites-sand soil with proportion 60:40.

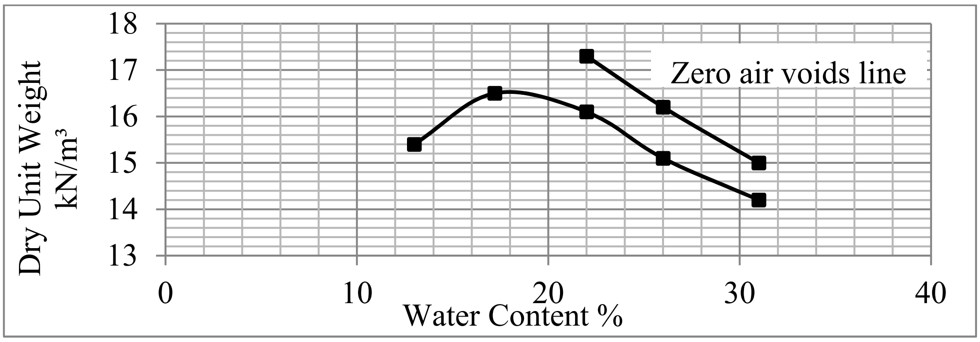

Figure (5): Compaction curve of bentonites-sand soil with proportion 50:50.

Testing program

Depending on the results of the compaction curve, two points have been chosen (one from the dry side and the other at optimum moisture content) for all types of soil to measure the swelling potential, the expansion index, the swelling pressure, the consolidation behavior, the unconfined compressive strength and the coefficient of permeability by taking specimens from a large scale model which was prepared in a soil container with dimensions of (700*700*800) mm. Table (4) shows the water content and the dry unit weight used to prepare the samples.

The natural sand was firstly air dried and then sieved at sieve No.10, because the bentoniteh as the ability to absorb water up to 6 % moisture content during storage at ambient humidity and temperature, so it was also decided to dry the samples by an oven at 110°C before use. The soils were allowed to cool down to room temperature, then mixed thoroughly with the required amount of water by hands, and then kept inside plastic bags for a period not less than five days to get uniform moisture content (Agus*et al.*, 2010 and Vanapalli and Taylan, 2012).

Table (4): Water content and dry unit weight of the soil samples.

Soil type	Water content %	γ_{dry} (kN/m³)	Void ratio (e)	Degree of saturation % (S)
Pure bentonite	25	12.4	1.29	55
Pure bentonite	34	12.75	1.23	78.5
B:S (70:30)	20	14.67	0.92	61
B:S (70:30)	27	15.1	0.86	88
B:S (60:40)	18	15.6	0.79	64
B:S (60:40)	22	15.9	0.76	81
B:S (50:50)	15	16	0.74	56.6
B:S (50:50)	18	16.6	0.68	74

The swelling test and modified free swell index

The swelling test was carried out to measure swelling potential, expansion index and swelling pressure according to ASTM D4829-03 and Head, (1994). In this test, the oven dried soil passing 2 mm sieve was mixed with the required amount of water as determined previously and was remolded at the standard compaction mould to three equal layers to achieve the required density and then inserting the oedometer ring (75 mm in diameter and 20 mm in height) to extrude the sample, but the height of the specimen must be less than the height of the consolidation ring so as to ensure that the specimen remains laterally confined as it swells, so the height of the specimen was 15 mm as recommended by Head, (1994).

A load of 7 kPa was placed as a seating load; the specimen was allowed to consolidate under this pressure for a period of ten minutes, after this time the initial reading was recorded. The soil sample was submerged in distilled water for 24 hours then the final reading was recorded. To measure the swelling pressure, weights would be added in increments to the soil sample to get zero dial gauge reading.

The modified free swell index suggested by Nelson and Miller (1992) was evaluated to get an indication about the swelling potentials of the soil used. This test involves obtaining an oven-dried soil with a mass of about 10 grams. The soil mass was transferred into a 100-ml graduate containing distilled water and measuring the swollen volume after it has completely settled. The free swell index of the soil is determined as the ratio of the change in volume to the initial volume, expressed as a percentage.

One-dimensional consolidation test

One-dimensional consolidation test was carried out at the end of the swelling pressure test according to ASTM D 2435-96 and performed for the four types of soil with the two dry densities. From the one dimensional consolidation test result, the coefficient of permeability was calculated according to the following equation:

$$k = c_v \, m_v \gamma_w \qquad (1)$$

where: c_v = the coefficient of consolidation,

m_v= the coefficient of volume change and,

γ_w= the unit weight of water.

Unconfined compression test

The unconfined compression test was performed according to ASTM D 2166-00. This test is basically used to find the unconfined compressive strength (q_u) of the soil by which the shear strength of the soil can be computed as:

$$c_u = q_u/2 \qquad (2)$$

where: cu = the soil cohesion.

Permeability test

For measuring the permeability of soils of intermediate and low permeability (less than 10^{-4} cm/sec), i.e. silts and clays, the falling head procedure was used which was done according to Head, (1994) by inserting the core cutter (cell body) into the soil after completing the test of large scale model prepared for saturation of samples. The model size of the soil is (700*700*650) mm, the samples were taken from 20 cm depth from the surface Plate.

Results and Discussions

This section demonstrates the results obtained from experiments carried out to measure the swelling index, swelling pressure, unconfined compressive strength and coefficient of permeability.

To simplify the observations of the soil samples that will be dealt with in the experimental work, symbols are used to characterize each soil. Table (5) shows soils used and their symbols.

Table (5): Soil types and their symbols.

Type of soil	Sample ID	Degree of saturation % (S)	Water content %	Dry unit weight (kN/m^3)
Pure Bentonite	B1	55	25	12.4
	B2	78.5	34	12.75
Bentonite:Sand 70:30	BS1	61	20	14.67
	BS2	88	27	15.1
Bentonite:Sand 60:40	BS3	64	18	15.6
	BS4	81	22	15.9
Bentonite:Sand 50:50	BS5	56.6	15	16
	BS6	74	18	16.6

Results of swelling test and modified free swell index

Table (6) shows the results of the swelling potential, expansion index and swelling pressure obtained from the swelling test which was carried out for each soil using two different initial water contents.

The swelling potential is calculated as:

$$\text{Swelling potential\%} = \Delta H/ H_i \text{ x}100 \qquad (3)$$

Where: ΔH = the change in sample height, D_2-D_1,
H_i = the initial sample height,
D_1 = the initial dial reading mm, and
D_2 = the final dial reading mm.

But the expansion index (EI) can be found according to ASTM 4829-03 as follows:

$$EI = \Delta H/Hi \text{ x}1000 \qquad (4)$$

The results show that the swelling percent increases with increasing the initial void ratio due to decrease in the initial water content which is the main factor for the capability of swelling because its capacity to absorb water deceases with increase of its degree of saturation (Murthy, 1989).

The expansion index and swelling pressure for the four types of soils decrease with increase in the initial water content of the soil and that due to the structure of the soil which is more dispersed at high moisture contents, the soil tend to imbibe water to satisfy the double layer and this condition decrease with increasing water content (Sudjianto*et al*., 2009).

These results are in good agreement with Kassif*et al.* (1962), Chen (1975) and Day (2006) who proposed relationships based on experimental data for swelling potential and initial soil state parameters such as initial dry density and initial water content. They found that swelling potential depends on both initial water content and dry density. It increases with increasing initial dry density at constant water content and decreases with increasing initial water content at constant dry density. The results are also compatible with the findings of Zumrawi (2013) who studied the effect of the initial state parameters of soil such as water content, dry density and void ratio which were combined in a way reflecting the influence of each of them on swelling potential.

According to Warkentin (1962) and Vikas and Devendra (2005), who studied the swelling of soil by performing oedometer testing, the swelling pressure decrease with increasing the soil initial water content.

Chen (1975) stated that the initial molding water content has a greater influence on the soil swelling potential than the initial void ratio. It was also stated that the lower the initial void ratio, the higher will be the swelling pressure when the initial water content is constant.

The results also state that the swelling percent decreases with increase of sand content and when the swelling potential decreases from 14% to 2.4% by adding 50% sand to pure bentonites. This is in good agreement with Chalermyanont and Arrykul (2005) and it is interpreted to the existence of the interlayer of montmorillonite which absorbs the water causing an increase in its volume and after the water uptake, the voids will be filled by the swollen montmorillonite.

Table (6): Results of swelling test.

Sample ID	Swelling Potential %	Expansion Index	Swelling Pressure (kPa)
B1	16	160	200
B2	14	140	162.5
BS1	12	120	125
BS2	9.3	93	87.5
BS3	7.2	72	50
BS4	5	50	37.5
BS5	3.6	36	25
BS6	2.4	24	12.5

The results of the modified free swell index are presented in Table (7) which show that the potential of soil for swelling increases with increase of the plasticity index of the soil which lead to an increase in the soil activity and the specific surface for swelling. The classification of soil due to free swell index according to Sivapullaiah*et al.* (1996) is given in Table (8).

Table (7): Results of the modified free swell index.

Type of soil	Plasticity index (%)	Modified free swell index (%)	Swelling potential according to Sivapullaih e*t al. (1996)*
Pure bentonite	81	23	Very high
B:S, 70:30	59	19	High
B:S, 60:40	46	13	High
B:S, 50:50	30	5	Moderate

Table (8): Qualitative classification of expansive soils, (Sivapullaiah*et al.*, 1996).

Modified free swell index (%)	Swelling potential
< 2.5	Negligible
2.5-10	Moderate
10-20	High
> 20	Very high

Results of one-dimensional consolidation test

One-dimensional consolidation test was carried out using four types of soil which was prepared at two initial water contents; one at dry side and the other at optimum moisture content and the results are shown in Table (9).

The results show that, the compression index c_c and the coefficient of consolidation c_v of the soil increase with decrease of the plasticity index, this is due to the thickness of diffuse double layer which will be relatively larger for a highly plastic soil as compared to a less plastic soil. The thicker the diffuse double layer, the greater the reduction in the effective pore size for flow. This may cause the hydraulic conductivity values to be relatively higher for less plastic soils than for more plastic soils as recommended by Fredlund (1969). While recompression index c_r or swelling index c_s for the plastic soil decreases with increase of the sand proportion. This is due to the decrement of the specific surface and the soil activity for swelling.

Table (9): Results of one-dimensional consolidation test for different soils.

Soil property	Pure Bentonite		B:S 70:30		B:S 60:40		B:S 50:50	
	B1	B2	BS1	BS2	BS3	BS4	BS5	BS6
Compression index, cc	0.27	0.28	0.29	0.3	0.3	0.34	0.36	0.4
Recompression index, cr	0.065	0.054	0.052	0.046	0.042	0.038	0.036	0.035
Coefficient of volume compressibilit, mv (m^2/kN)	1.25* 10^{-4}	1.35* 10^{-4}	1.78* 10^{-4}	2.1* 10^{-4}	2.2* 10^{-4}	2.51* 10^{-4}	2.75* 10^{-4}	3.2* 10^{-4}
Coefficient of consolidation, cv (m^2/sec.) under pressure of 200 kPa	2.3* 10^{-8}	2.64* 10^{-8}	4.1* 10^{-8}	4.6* 10^{-8}	5.6* 10^{-8}	6.2* 10^{-8}	6.6* 10^{-8}	7.4* 10^{-8}
Coefficient of permeability, k (m/sec.)	2.9* 10^{-11}	3.56* 10^{-11}	7.3* 10^{-11}	9.7* 10^{-11}	1.3* 10^{-10}	1.6* 10^{-10}	1.8* 10^{-10}	2.4* 10^{-10}

Unconfined compression test results

Eight unconfined compression test were conducted using four types of soils at two states: the first at dry side of compaction curve and the second at optimum moisture content obtained from standard Proctor test of each soil.

The results of the four types of soil: pure bentonite and bentonite: sand mixtures with proportions (70:30, 60:40 and 50:50) % of dry weight are shown in Figures (6) to (9), respectively. The results demonstrate that the undrained shear strength (c_u) decreasesfrom 278.5 kPa to 88 kPa with increasing water content from 25% to 34% as shown in Figure (6). The same behavior was found for the other types of soils. The behavior of the results is in agreement with the results of Fredlund*et al.* (1995) who found that the shear strength increases with matricsuction using closed-form solution. The results are also compatible with Vogrig*et al.* (2003) who proposed an estimation to the resilient modulus of unsaturated soil specimens from CBR and unconfined compression test. Their results showed a regular trend of increase in shear strength of the soil specimens with a decrease in the degree of saturation. The results are also comparable with those of Garven and Vanapalli (2004) who undertaked a comprehensive analysis to predict the variation of shear strength with respect to matric suction of twenty soils utilizing the six prediction equations that use SWRC, Al-Mukhtar*et al.* (2006) who compared between the measured and estimated unconfined compressive strength for two lime stones, Tuffeau stone and Sébastopol stone, Changis*et al.* (2010) who studied the properties of unsaturated loessial soils based on extensive laboratory data including compaction, CBR, strength, deformation and suction and Ye *et al.* (2010) who also studied the unsaturated weakly expansive clay by employed soil-nature property testes and some unsaturated triaxial tests with suction control.

Matric suction is one of the stress state variables that control the shear strength of unsaturated soils, (Farouk *et al.*, 2004).

The results show that the increase in matric suction did not affect the general shape of the stress-strain relationship.

According to Chowdhury (2013), the shear strength increases with respect to an increase in matric suction which is defined by the angle $ø^{b}$. At zero suction, $ø^{b}$may assume to be the saturated friction angle, then the $ø^{d}$ecreases with the increase in matric suction. It appears that the angle is a function of matric suction.

The interpretation of this phenomenon is that, at low matric suction, air enters the pores and a contractile skin begins to form around the points of contacts between particles. The capillary action arising from suction at the contractile skin increases the normal forces at the inter-particle contacts. These additional normal forces may enhance the friction and the cohesion at the inter-particle contacts, (Farouk *et al.*, 2004).

The unconfined compressive strength (q_u) of pure bentonite soil is higher than that of bentonite: sand soil due to the higher suction in the pure bentonite soil compared to other types of soils which causes increase in the soil strength.

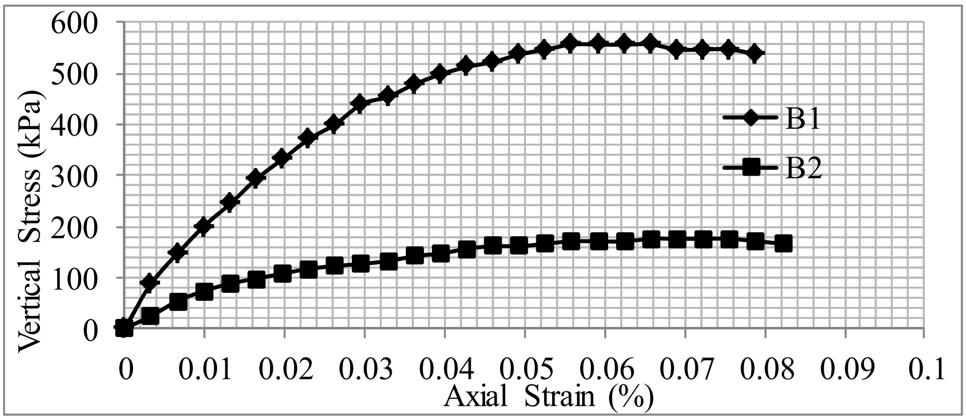

Figure (6): Unconfined compression test results of pure bentonite at different water contents.

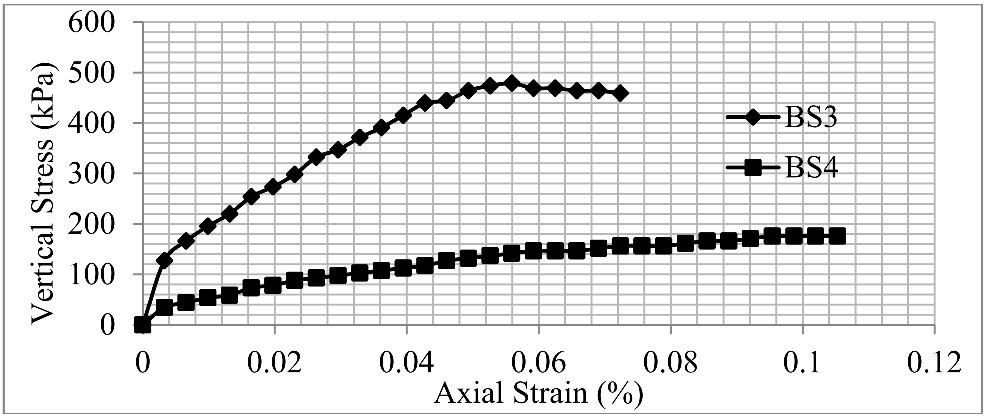

Figure (7): Unconfined compression test results of B:S mixture with proportion 70:30 at different water contents.

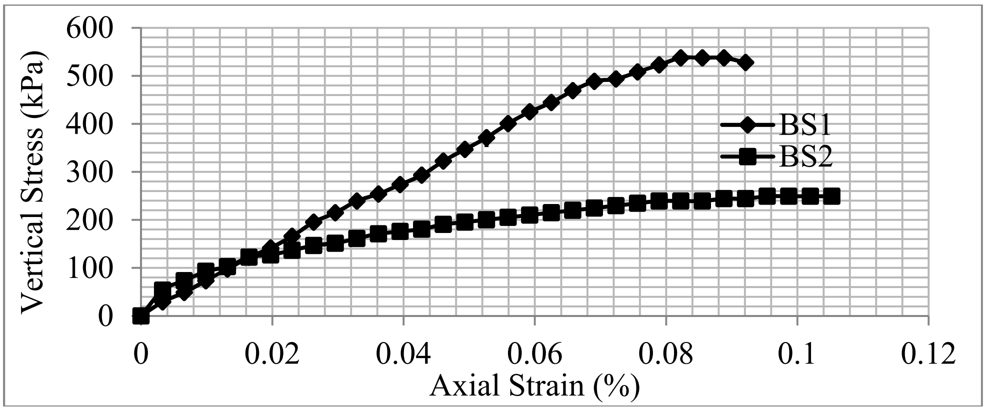

Figure (8): Unconfined compression test results of B:S mixture with proportion 60:40 at different water contents.

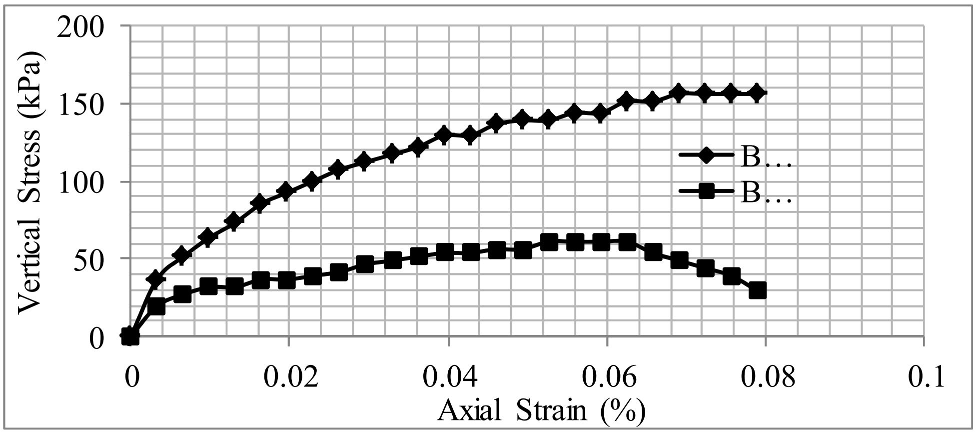

Figure (9): Unconfined compression test results of B:S mixture with proportion 50:50 at different water contents.

Influence of degree of saturation on the coefficient of permeability

The coefficient of permeability was found for initial condition and for the soil model at the end of the test by one-dimensional consolidation test from eq. (1) and by falling head permeability test, a core cutter (cell body) was inserted in the soil model after completing the test of large scale model at 20 cm depth from the surface and a sample was taken for permeability test respectively. Figure (10) shows the variation of log coefficient of permeability with degree of saturation, there is a steep decrease of permeability with decrease of the degree of saturation. This is due to volume-mass relation between soil grains, water and gas will change, the permeability coefficient will have distinct change in the course of non-stable transition. The effect of change of void ratio of unsaturated soil on the coefficient of permeability is a minor factor, while the influence of saturation is remarkable. These results are in good agreement with Cattoni*et al.* (2005) who focused his study to investigate the mechanical behavior of unsaturated pozzolona by employed isotropic and triaxial compression tests, McCartney *et al.* (2007) who performed an infiltration column test on a clay specimen to obtain hydraulic conductivity function (k-function), Romero and Simms (2008) who studied the microstructure of partially saturated soil, by utilizing mercury intrusion porosimetry and the environment scanning electron microscopy, Jun-me and Hai-ning (2010) who made a comparison between the measured and estimated coefficient of permeability using triaxialapparatus controlled by stress and strain to measure matric suction and volumetric water content, and Hashem (2013) who proved that in saturated soil, all the pore spaces between the particles are filled with water, while the air filled pores in unsaturated condition. This phenomenon increases the toruosity of the flow path. As a result, the ability of the soil to transport water decreases, as stated by Ito *et al.* (2014) who developed a two stage deformation model by simultaneously calculating soil suction and stress state. The model predictions were validated using a one-year field monitoring data. The coefficient of permeability of the unsaturated B:S mixture with proportion 50:50 decreases more sharply when compared with the other soils as the degree of saturation decrease and this is attributed to the larger desaturation rate of the soil, since air filled pores are non-conductive channels to the flow of water. A sharp reduction in coefficient of permeability due to decrease of water which leads to increase in the matric suction was found by McCartney*et al.* (2007) and Ng and Menzies (2007).

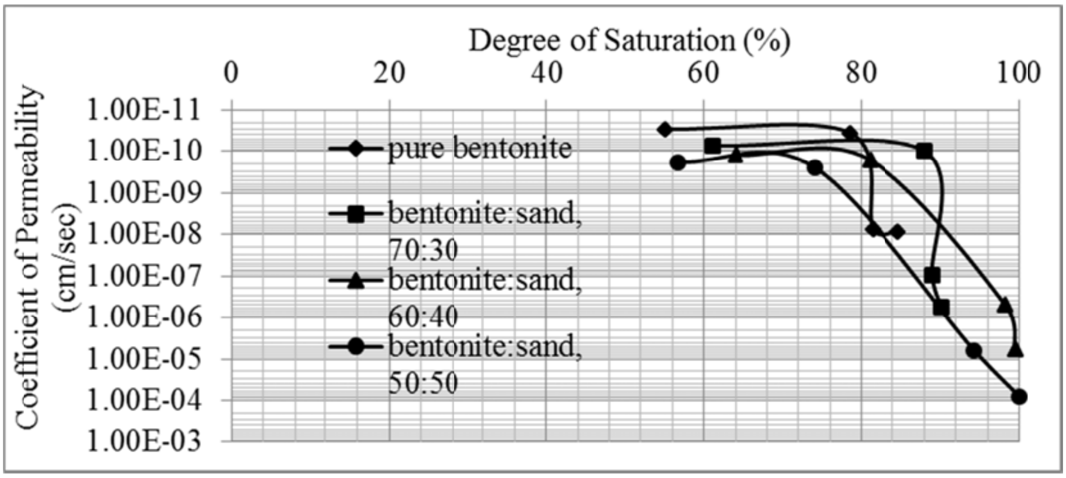

Figure (10): The variation of coefficient of permeability with degree of saturation for differenttypes of soil.

CONCLUSIONS

Based on the experimental results, the main points concluded are as follows:

1. From the conventional swelling test results, the swelling potential, expansion index and the swelling pressure decrease with increase in the initial water content of the soil due to the structure of the soil which is more dispersed at high moisture contents and at the natural condition, the soil tend to imbibe water to satisfy the double layer and this condition decrease with increasing water content.
2. The swelling percent decreases with increase of sand content, and that is true when the swelling potential decreases from 14% to 2.4% by adding 50% sand to pure bentonites.
3. The compression index c_c and the coefficient of consolidation c_v of the soil increase with decrease of the plasticity index, however, the c_c increases from 0.271 to 0.364 when the plasticity index decreases from 81% to 30%. On the other hand, the c_v increases approximately three times when adding 50% of sand to pure bentonites. While, the recompression index c_r or the swelling index c_s for the plastic soil decreases with increase of the sand proportion from 0.065 to 0.052 when the bentonite content was decreased to 70%.
4. The shear strength increases with the decrease the in initial water content and increase of the soil suction. The soil strength decrease to the third when the initial water content changes from 25% to 34% for pure bentonite soil. Moreover, the decrease of the soil suction from 82 kPa to fully saturation leads to decrease the soil strength from 268.5 kPa (very stiff) to 20.5 kPa (very soft) for soil 70:30 (bentonite: sand) mixture with 20% water content.
5. With decrease of the degree of saturation, there is a steep decrease of permeability and this is due to volume-mass relation between soil grains, water and gas, however the permeability coefficient increases from $1.82*10^{-10}$ cm/sec to $8.1*10^{-5}$ cm/sec when the degree of saturation increases from 57% to 99.9% for the bentonite mixed with sand with proportion 50:50.
6. The coefficient of permeability values relatively higher for less plastic soils than for more plastic soils and this is due to the thickness of diffuse double layer which will be relatively larger for a highly plastic soil as compared to a less plastic soil. The thicker the diffuse double layer, the greater the reduction in the effective pore size for flow.

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